

Is there a population of unidentified gamma-ray sources distributed along the super-galactic plane?

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ABSTRACT

The distribution on the sky of unidentified sources at the highest energies where such a population is evident is investigated. For this purpose, sources without identification in the first Fermi-LAT catalog >10 GeV (1FHL) that are good candidates for detection above the 50–100 GeV regime are selected. The distributions of these objects around the Galactic and super-galactic plane are explored. By using a Kolmogorov-Smirnov test it is examined if these sources are distributed homogeneously around these planes. Surprisingly, an indication for an inhomogeneous distribution is found for the case of the super-galactic plane where a homogeneous distribution can be excluded by a confidence level of 95%. On a 90% confidence level also a homogeneous distribution of sources around the Galactic plane can be excluded. For the hypothesis that this reflects the true distribution of sources rather than a statistical fluctuation, implications for the underlying source populations are discussed.

Key words: radiation mechanisms: non-thermal - cosmic rays - gamma-rays: general

1 INTRODUCTION

The distribution on the sky is a powerful tool to explore the nature and distance scale of unidentified astrophysical sources. It has already been applied to steady (e.g. Gehrels et al. 2000; Aharonian et al. 2006) and transient sources (e.g. Meegan et al. 1992; Foley et al. 2008; Thornton et al. 2013). Alignment with prominent features on the sky like the Galactic plane or local galaxies or galaxy clusters may connect the sources to these structures. A homogeneous distribution may either point to an origin in the solar neighborhood on the one extreme of possible distance scales or to a cosmological origin on the other extreme.

The aim of this work is to investigate the distribution on the sky of unidentified sources at the highest energies where such a population is evident. Several unidentified sources radiating in the energy regime between 10–100 GeV have been reported from the *Fermi* satellite (The first Fermi-LAT catalog of >10 GeV sources (1FHL) Ackermann et al. 2013). A subsample of the 1FHL sources has been flagged for being good candidates for detection above the 50–100 GeV regime. Sources selected in this way are here used as a proxy for the distribution of such sources in the very-high energy (VHE, $E>100$ GeV) gamma-ray band. The distribution on the sky of these sources is investigated in this work.

H.E.S.S. has discovered an unidentified VHE gamma-ray source with a significant off-set from the Galactic plane: HESS J1507-622 (Acero et al. 2011). Despite significant observational and theoretical effort the nature of the source still remains elusive (Domainko 2011; Domainko & Ohm 2012; Vorster et al. 2013; Tibolla et al. 2014; Eger et al. 2014). Sources that are good candidates for detection in the 50–100 GeV regime in the 1FHL catalog appear similar in their GeV properties to 1FHL J1507.0-6223,

the *Fermi* counterpart of HESS J1507-622. So far the relation between these sources and HESS J1507-622 is not known. The *Fermi* counterpart of this source has been reported as being point-like (Acero et al. 2013), however, it has to be noted, that HESS J1507-622 is clearly extended in the VHE regime. In this paper also the implications for the case are discussed where HESS J1507-622 is a representative of a source class that is similarly distributed on the sky as the 1FHL sources that are good candidates for detection above the 50–100 GeV regime.

2 SAMPLE SELECTION

For the purpose of this work, the subsample of the 1FHL that are good candidates for detection at energies above 50–100 GeV and lack an identification is selected as source sample. The advantage of using the 1FHL catalog is the fact that it provides a homogeneous sky coverage. None of these sources has been flagged as being variable.

Good candidates for detection above 50–100 GeV may in principle belong to a similar object type as HESS J1507-622. Contrary to HESS J1507-622 all unidentified sources detected in the VHE gamma-ray range with H.E.S.S. are located very close to the Galactic plane (within $\pm 1^\circ$ of the Galactic plane, see Aharonian et al. 2008). At this point it is not clear if HESS J1507-622 is a representative of this source population or if it is a member of a different type of objects with a different distribution on the sky (see also Eger et al. 2014, for a discussion). Here the second possibility is explored.

It is investigated whether there is an indication for a population of sources, that may belong to an old stellar population (as in-

Table 1. Unidentified sources from the 1FHL catalog that are good candidates for detection above the 50-100 GeV regime. The region of $\pm 1^\circ$ around the Galactic disk is excluded.

1FHL name	SGL	SGB	l	b
J0030.1-1647	278.6	1.2	96.3	-78.6
J0053.9+4030	335.8	10.3	123.4	-22.4
J0110.0-4023	257.7	-12.9	287.9	-76.2
J0307.4+4915	353.0	-7.9	144.6	-7.8
J0312.8+2013	328.1	-24.7	62.5	-31.6
J0338.4+1304	324.4	-33.5	73.5	-32.9
J0425.3+6320	10.5	-5.8	144.4	9.8
J0425.4+5601	6.2	-11.7	149.7	4.7
J0432.2+5555	6.9	-12.4	150.5	5.3
J0439.9-1858	285.7	-57.7	216.9	-37.2
J0509.9-6419	220.6	-38.2	274.3	-35.2
J0601.0+3838	13.7	-34.2	173.2	7.6
J0639.6-1244	335.0	-85.3	223.0	-8.3
J0650.4+2056	24.8	-53.3	194.0	9.2
J0746.3-0225	71.3	-71.7	221.5	11.1
J0803.4-0334	82.5	-69.3	224.6	14.2
J1115.0-0701	116.7	-25.9	265.1	48.6
J1129.2-7759	194.6	-19.8	298.6	-15.8
J1240.4-7150	187.5	-16.1	302.1	-9.0
J1315.7-0730	125.1	2.9	313.4	54.9
J1328.5-4728	164.2	-6.0	309.4	14.9
J1353.0-6642	183.6	-8.8	309.0	-4.6
J1406.4+1646	104.2	21.1	6.0	69.8
J1440.6-3847	161.4	9.4	325.2	19.3
J1507.0-6223	183.6	0.2	317.9	-3.5
J1545.2-6640	189.5	0.5	319.0	-9.3
J2004.7+7003	19.3	34.6	102.9	19.5
J2036.9-3325	232.5	35.2	9.7	-35.5
J2159.1-3344	247.4	23.9	12.0	-52.6

indicated by their off-set from the Galactic plane) and whether there is any indication for a non-uniform distribution on the extragalactic sky. Therefore, the region of $\pm 1^\circ$ around the Galactic disk is excluded from the selection of the source sample. These sources are very likely of galactic origin and most likely connected to a young stellar population. This results in a selection of 29 sources (see Tab. 1). For a homogeneously distributed sample of 29 sources on the sky only 0.5 sources would be expected within $\pm 1^\circ$ of the Galactic plane.

3 DISTRIBUTION OF THE SOURCES

HESS J1507-622 is located close to both the Galactic and the super-galactic plane ($b \approx -3.5^\circ$, $SGB \approx 0.2^\circ$). In the following it is investigated how the selected source sample is distributed with respect to these two planes. In all cases a Kolmogorov-Smirnov (KS) test is used to check if the sources are homogeneously located around a given plane.

3.1 Galactic plane

The KS test has been applied to test if the selected sample of sources is distributed homogeneously around the Galactic plane (see Fig. 1). As a result of this test the maximum off-set D_{max} of the cumulative probability of the sources from the prediction for a homogeneous distribution is 0.230 for 29 sources. Therefore, the hypothesis of a homogeneous distribution can be rejected by a confidence level of 90%.

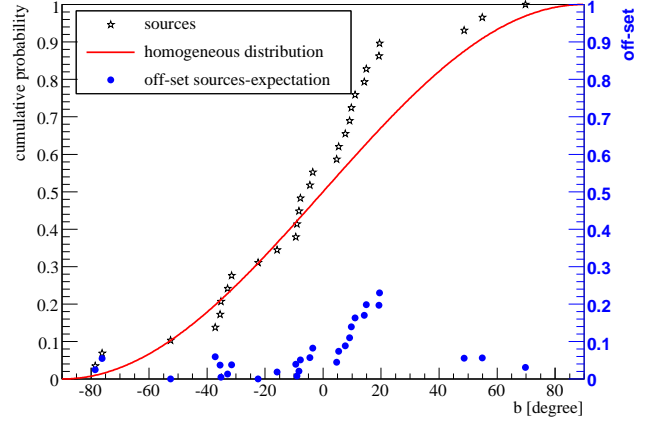


Figure 1. Kolmogorov-Smirnov test for the distribution of the sources of Tab. 1 around the Galactic plane. The largest off-set from a homogeneous distribution D_{max} is 0.230.

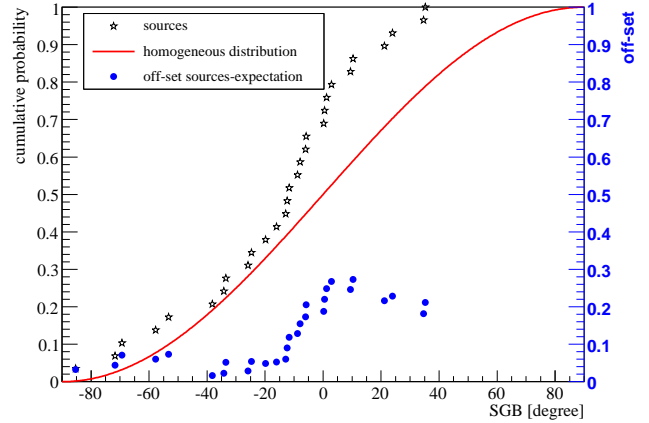


Figure 2. Same as Fig. 1 but for the super-galactic plane. D_{max} is 0.273.

3.2 Super-galactic plane

The super-galactic plane is the plane on the sky where galaxies with distance up to a few 10s of Mpc cluster (deVaucouleurs et al. 1976; Lahav et al. 2000). The same procedure as in Sec. 3.1 has been applied for the distribution of sources around the super-galactic plane. There D_{max} is found to be 0.273. Consequently, the hypothesis of a homogeneous distribution can be rejected at a confidence level of 95%.

3.3 Discussion

Clustering of sources around the Galactic plane is expected due to the presence of Galactic objects whereas a concentration of unidentified sources around the super-galactic plane is rather unexpected. Therefore, here it is investigated if the apparent inhomogeneous distribution of sources is artificially generated by potential inhomogeneous detection efficiency by *Fermi* across the sky.

From the sample of selected sources it is evident, that there is a deficit of sources in the direction of the super-galactic north-pole. The super-galactic north pole is located in Galactic coordinates in the direction of $l = 47.37^\circ$ and $b = +6.32^\circ$ and thus rather close to

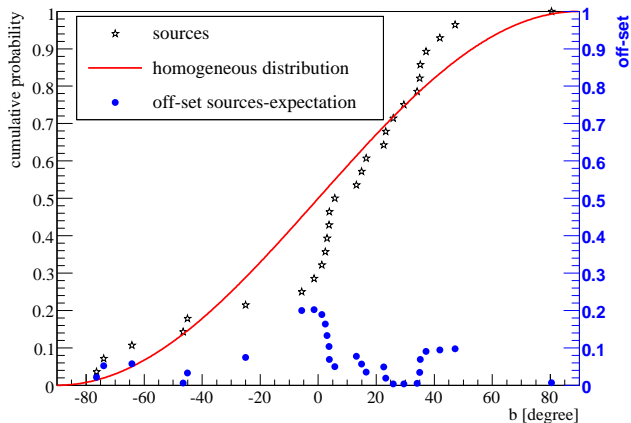


Figure 3. KS test for the distribution of unidentified sources from the 1FHL catalog that are not flagged for being good candidates for detection above 50-100 GeV around the Galactic plane. D_{max} is 0.202.

the Galactic plane (deVaucouleurs et al. 1976; Lahav et al. 2000). Two effects may be important there. On the one hand source detection might be affected by the presence of Galactic diffuse emission. On the other hand, since there is some indication of sources clustering around the Galactic plane, it could actually be expected to find an excess of sources at low Galactic latitudes (and also in the direction of the super-galactic north pole). These two effects work in opposite directions. To test if there is any bias of this kind, the same procedure as in Sec. 3.1 and 3.2 is applied to unidentified sources in the 1FHL that were not flagged to be good candidates for detection above 50-100 GeV. It would be expected that detection efficiency for these sources is biased in a comparable way as for the sample of sources defined in Sec. 2. Again, sources with Galactic latitudes in between $\pm 1^\circ$ were excluded (see Sec. 2). This procedure selects a sample of 28 sources. The result of a KS test for these sources is shown in Fig. 3 (for the Galactic plane) and Fig. 4 (for the super-galactic plane). The D_{max} found for this sample of sources is 0.202 (Galactic plane) and 0.110 (super-galactic plane). As a result, the location of these sources with respect to the super-galactic plane is compatible with a homogeneous distribution. Therefore, it is unlikely that the indication of an inhomogeneous distribution found for the sample of sources given in Tab. 1 is introduced by an inhomogeneous detection efficiency of *Fermi*.

Additionally, it is investigated if there is any correlation between the Galactic latitude and the super-galactic latitude of the sources in Fig. 5. As a result, no evidence of an obvious correlation is found. The reason for the deficit of sources in the direction of the super-galactic north-pole is not known at the moment.

Finally, the same procedure as in Sec. 3.1 and 3.2 is applied to the sample of 36 high-energy neutrino events detected by IceCube (Aartsen et al. 2014). As a result of this investigation a D_{max} of 0.143 (Galactic plane) and 0.103 (super-galactic plane) is found and thus the distribution of events is consistent with a homogeneous distribution for both cases.

To conclude, there are moderately significant indications that sources from the sample defined in Sec. 2 are inhomogeneously distributed with respect to both, the Galactic and the super-galactic plane. Rather surprisingly, the strongest indication for an inhomogeneous distribution is found for the case of the super-galactic plane for the sources of Tab. 1.

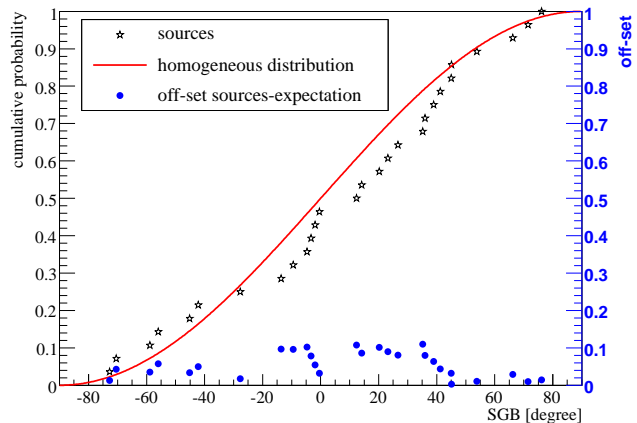


Figure 4. Same as Fig. 3 but for the super-galactic plane. D_{max} is 0.110.

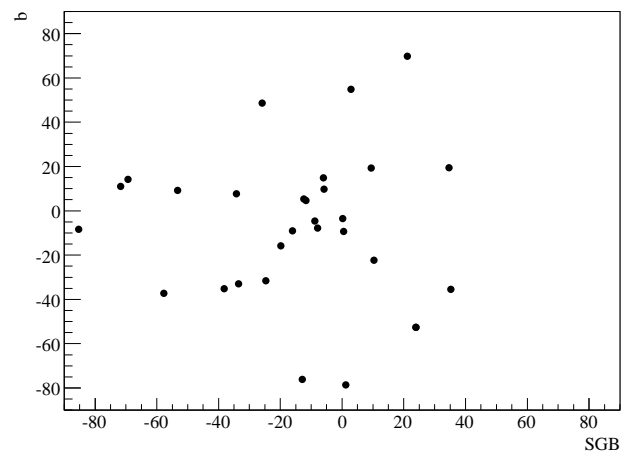


Figure 5. Correlation between the Galactic and the super-galactic latitude of the sources from Tab. 1. No clear correlation between these two quantities is seen.

4 IMPLICATIONS

For this Section it is assumed that the inhomogeneous distribution of sources with respect to the Galactic and super-galactic plane is not a statistical fluctuation but rather reflects the true distribution of sources.

4.1 Galactic origin

The discussion in this section is based on the hypothesis that some of the sources located in the vicinity of the Galactic plane from the sample defined in Sec. 2 are of similar origin as HESS J1507-622. It has to be noted that at the moment it is not clear whether such a connection exists. The extended nature of HESS J1507-622 in the VHE gamma-ray range would favor a Galactic origin.

HESS J1507-622 is likely located at multiple-kpc distance as indicated by its compact appearance (Acero et al. 2011; Domainko & Ohm 2012) and its considerably absorbed potential X-ray counterpart (Eger et al. 2014). For the following discussion it is assumed that some of the sources in the sample defined in Sec. 2 are located at a comparable distance.

The typical flux above 10 GeV of these sources is about $5 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Ackermann et al. 2013), resulting in a luminosity of about $10^{34} (d/5 \text{ kpc})^2 \text{ erg s}^{-1}$, with d being the typical distance to these objects. Assuming IC up-scattering of CMB photons by highly energetic electrons as the dominating radiation mechanism (cooling time of electrons with energy of 300 GeV of about 3×10^6 years, Hinton & Hofmann 2009) then the energy in electrons would be about $10^{48} (d/5 \text{ kpc})^2 \text{ erg}$. The off-set for sources located close to the Galactic plane in Tab. 1 is typically a few degrees. For a multi-kpc distance this would result in a Galactic scale height of these sources of several hundred parsecs. To summarize, the energetics of the sources would be in line with the typical energetics of known types of VHE gamma-ray emitters (Hinton & Hofmann 2009) whereas the Galactic scale height would be much larger than the typical scale height of a young stellar population (see e.g. Grégoire & Knödlseider 2013; Domainko 2014).

Finally, if it is assumed that $O(10)$ such sources exist in the Galaxy and their typical age is about 10^6 years (see Eger et al. 2014, for a discussion on HESS J1507-622), then the typical rate for their formation would be 10^{-5} yr^{-1} for the Galaxy or $100 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (assuming a density of Milky Way-type galaxies of 0.01 Mpc^{-3} , Cole et al. 2001).

4.2 Extragalactic origin

Firstly, and more generally, here the implications of a source population connected to the super-galactic plane is explored. The typical distance of galaxies that form the super-galactic plane is a few tens of Mpc (Lahav et al. 2000). Therefore, for $O(10)$ such sources their volume density would be roughly $4 \times 10^{-5} (d/30 \text{ Mpc})^{-3} \text{ Mpc}^{-3}$. Such a distance scale would result in a typical un-beamed source luminosity of $5 \times 10^{41} (d/30 \text{ Mpc})^2 \text{ erg s}^{-1}$ and typical energy in electrons of $5 \times 10^{55} (d/30 \text{ Mpc})^2 \text{ erg}$ if again it is assumed that IC up-scattering of CMB photons by highly energetic electrons is the dominating radiation process. These energy requirements are very challenging for galactic type sources but can easily be accommodated by active galactic nuclei. In principle the energetics would be reduced if the emission is significantly beamed (as it is the case for example for BL Lac type objects).

In this extragalactic scenario it is interesting to investigate if the sources from Tab. 1 are located at the position of nearby galaxies. This search has been conducted by using the NASA/IPAC extragalactic database¹. Only for one case (1FHL J2159.1-3344) a galaxy with a distance of less than 50 Mpc (GALEXASC J215915.26-335251.9, angular distance of $8.4'$ $z = 0.0097$, $D \approx 40 \text{ Mpc}$, Jones et al. 2009) has been found within $10'$ of the source. If the distance is increased to 100 Mpc, galaxies inside an angular radius of $10'$ for two more sources are found (1FHL J0053.9+4030, CGCG 536-006, angular distance $5.5'$ $z = 0.019$, $D \approx 80 \text{ Mpc}$, Strauss et al. 1992) and (1FHL J1406.4+1646, SDSS J140701.68+164232.8, angular distance $9.1'$ $z = 0.016$, $D \approx 67 \text{ Mpc}$, Sanchez Almeida et al. 2011). As a result, it appears, that there is no strong correlation between the sources from Tab. 1 and nearby galaxies.

Secondly, and more specifically, the implications of a population of extragalactic sources with similar properties as HESS J1507-622 is investigated. An extragalactic scenario may in principle be motivated by the large required distance to the object if the energy density in particles and in the magnetic field are

roughly equal (Domainko 2014). The spectral parameters found by Eger et al. (2014, energy in electrons $5 \times 10^{47} (d/1 \text{ kpc})^2 \text{ erg}$, magnetic field $0.47 \mu\text{G}$) would result in an equipartition distance of about 30 Mpc, that is coarsely compatible to the typical distance of galaxies connected to the super-galactic plane. For a source age of 10^6 years (see again Eger et al. 2014), the rate of formation of such objects would roughly be $0.4 \times (d/30 \text{ Mpc})^{-3} \text{ Gpc}^{-3} \text{ yr}^{-1}$. The caveat for an extragalactic scenario for HESS J1507-622 is the fact that the angular extension of the source would require a physical extension of several tens of kpc. That is very challenging for a leptonic scenario (see Domainko 2014, for a discussion).

5 OUTLOOK

At this point inhomogeneities in the distribution of high-energy gamma-ray sources are found with moderate significance and its not clear whether this represents a statistical fluctuation or a real signal. One way to improve this situation is to perform multi-wavelength studies on some specific sources. To test the galactic scenario, sources that are located close to the Galactic plane are of enhanced interest. Good candidates would be: 1FHL J0425.4+5601 ($b \approx 4.7^\circ$) and 1FHL J1353.0-6642 ($b \approx -4.6^\circ$). To test the extragalactic scenario, sources that are located close to the super-galactic plane but are far from the Galactic plane may be important. These sources would be: 1FHL J0030.1-1647 ($b \approx -78.6^\circ$, $SGB \approx 1.2^\circ$) and 1FHL J1315.7-0730 ($b \approx 54.9^\circ$, $SGB \approx 2.9^\circ$). Follow-up observations of this kind may reveal if there is any source population connected to the Galactic and super-galactic plane.

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